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Technical Note

Numerical analysis and evaluation of an open-type thermal storage system using composite sorbents

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ABSTRACT

A family of composite sorbents has been acknowledged as promising thermal storage materials for low grade thermal energy storage owing to its high specific storage capacity and low regenerating temperature. This paper reports a simplified numerical model aiming to determine the dynamic characteristics of the composite sorbents and evaluate the specific capacity and COP of the open-type thermal energy storage system. The computational results were validated with the experimental measurements carried out on an open-type thermal energy storage set-up filled with composite sorbents. By using the simplified numerical model, the dynamic characteristics of the composite sorbents in the thermal energy storage process were determined. The effects of the composite sorbents and the operating parameters on thermal energy storage system performance were also evaluated.

1. Introduction

Thermal energy storage (TES) is an advanced technique to correct the mismatch between the supply and demand of energy [1–3]. The thermo-chemical technology based on water sorption/desorption on porous materials appears to be a promising candidate for TES since little heat loss occurs over the sorption storage process because of the temporally dissociation with adsorbate from adsorbent. Recently, a family of composite sorbents has been developed by impregnating the porous adsorbents to the aqueous solution of hygroscopic salts so as to improve their sorption and TES capacity [4–7]. The dynamic characteristics of the composite sorbents differ from the silica gels and zeolites. In point of determining the dynamic TES characteristics and optimizing the TES system performance, it is time- and energy-consuming to measure the TES characteristics through experimental investigations for different composite sorbents under various operating conditions. It will be helpful to establish a facile and feasible model and carry out numerical tests to optimize TES performance [8]. The majority of modeling undertaken so far concentrates on the pure adsorbents, e.g. silica gels and zeolites. Little work has been directed towards the dynamic TES characteristics of the composite sorbents by using a facile and feasible numerical model. The aim of this paper is to determine the dynamic characteristics of the composite sorbents and evaluate the performance of the open-type sorption TES through numerical tests based on a facile and feasible model. The simplified model was first validated by experimental measurements for the composite sorbents. Numerical tests were then carried out to determine the dynamic characteristics and evaluate the sorption TES performance.

2. Mathematical model

A typical open-type TES system mainly consists of an adsorber, a humidifier, and a condenser [6,7]. The adsorber is the key component of the sorption storage system where water is adsorbed on or desorbed from the sorbent. In order to simplify the model, the following assumptions are made: (a) the heat capacity of adsorbate in the adsorbed state is equal to that of the liquid phase; (b) the specific heat and density of dry composite sorbents are constant; (c) the composite sorbents are uniformly packed, and the adsorber can be considered as a packed bed with a certain porosity. It should be noted that the assumption (a) is feasible for an open-type TES system in this present study although the difference of the heat capacity between the adsorbate in the adsorbed state and that in liquid phase could be significant at high pressure and low temperature [9].

2.1. Energy conservation equation

The conservation equation of energy for the composite sorbents is

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$$m_{cs}\left(c_{p,dcs}+c_{p,w}w+\frac{m_b c_{p,b}}{m_{cs}}\right)\frac{\partial T_{cs}}{\partial t}-m_{cs}Q_{st}\frac{\partial w}{\partial t}=k_{cs}A_{cs}L\left(\frac{\partial^2 T_{cs}}{\partial x^2}+\frac{\partial^2 T_{cs}}{\partial y^2}+\frac{\partial^2 T_{cs}}{\partial z^2}\right)+\dot{S}_d \tag{1}$$

where m_{cs} and m_b are the mass of the composite sorbents and the adsorber heat exchanger, respectively. $c_{p,dcs}$, $c_{p,w}$, $c_{p,b}$ are the specific heat of the dry composite sorbents, water and the adsorber heat exchanger, respectively. w is the amount of water adsorbed on the composite sorbents, Q_{st} the isosteric heat of sorption, k_{cs} thermal conductivity of the composite sorbents, A_{cs} the heat transfer area for composite sorbents, L the length of the adsorber. $\dot{S}_d$ is the inner heat source item in terms of the heat input power ($q_{in} = 4$ kW at $T_{cs} < T_{pr}$, $q_{in} = 0$ at $T_{cs} \geqslant T_{pr}$, where T_{cs} and T_{pr} are the temperatures of the composite sorbents and the preset temperature for regenerating composite sorbents, respectively.) to regenerate the composite sorbents during the heat charging process. It is zero during the heat discharging process.

The conservation equation of energy for the air is

$$m_a c_{p,a}\frac{\partial T_a}{\partial t}=-\dot{m}_a c_{p,a}\frac{\partial T_a}{\partial x}+k_a A_a L\left(\frac{\partial^2 T_a}{\partial x^2}+\frac{\partial^2 T_a}{\partial y^2}+\frac{\partial^2 T_a}{\partial z^2}\right) \tag{2}$$

where, m_a, $\dot{m}_a$, $c_{p,a}$, k_a and A_a are the mass, mass rate, specific heat, thermal conductivity and heat transfer area of the air, respectively.

2.2. Adsorption equations

The mass transfer resistance of the inter-void space in the composite sorbents may be neglected. A linear driving force equation is introduced to determine mass transfer resistance of the composite sorbents. Thus the rate of change of moisture content is proportional to the difference between the equilibrium moisture content and the actual one.

$$\frac{\partial w}{\partial t}=h_m(w_{eq}-w) \tag{3}$$

where w_{eq} is the equilibrium amount of water adsorbed on the composite sorbents. h_m is the mass transfer coefficient and determined:

$$h_m=\frac{15D_s}{R_p^2} \tag{4}$$

where R_p is the average radius of composite sorbents. D_s is the surface diffusivity and can be expressed as a function of temperature:

$$D_s=\frac{1}{\xi}D_{s,0}\exp\left(-\frac{Q_{st}}{RT}\right) \tag{5}$$

where $D_{s,0}$ is the diffusivity with a constant value of 1.6×10^{-6} m^2/s. ξ is the bend factor relevant to the pore length of the composite sorbents.

2.3. Thermodynamic characteristics

The specific heat of composite sorbents is relevant to the amount of water adsorbed:

$$c_{p,cs}=c_{p,cs,dry}+wc_{p,w} \tag{6}$$

The heat of adsorption for composite sorbents can be obtained from the measurement of the sorption characteristics. It can also be fitted with a polynomial function of the amount of water adsorbed:

$$Q_{st}=a_4w^4+a_3w^3+a_2w^2+a_1w+a_0 \tag{7}$$

where the constants a_i ($i = 0, 1–4$) can be calculated by fitting the curve of heat sorption. For the composite sorbents prepared by impregnation the $CaCl_2$ solution with the mass concentration of 40% into the porous silica gel, the values of the constants has been calculated in our previous art [7] as: $a_4 = 1139$, $a_3 = -3307$, $a_2 = 3459$, $a_1 = -1620$, $a_0 = 2727$.

2.4. TES performance

The total heat input to regenerate the composite sorbents may be obtained by integrating of heat power over the heat charging period:

$$Q_{in}=\int_{chg} q_{in}\,dt \tag{8}$$

As the minimum temperature of the available heat output from the adsorber by air is preset to T_{avl}, the total heat output by the air over the discharging process can be calculated as

$$Q_{out}=\int_{dchg} c_{p,a}\cdot\dot{m}_a\cdot(T_{out}-T_{avl})dt \tag{9}$$

The specific TES capacity of composite sorbents can be accordingly calculated as

$$c_{ES}=\frac{Q_{out}}{m_{cs}} \tag{10}$$

The COP of the TES system is defined as

$$COP=\frac{Q_{out}}{Q_{in}} \tag{11}$$

3. Numerical solution and experimental validation

The governing equations were solved by using the finite volume method (FVM). The method imply that the integral conservations of quantities such as energy, mass and momentum are exact over any group of control volumes. The calculation domain was first divided into a finite number of non-overlapping control volumes. Then the discrete governing equations were derived over each control volume and time interval and numerically solved by using Fortran code.

An experimental open-type sorption storage set-up was built in Southern China to measure its TES performance to validate the computational results from the simplified numerical model. The dimensions of the adsorbent heat exchanger of the set-up are 0.8 m (length) × 0.3 m (width) × 0.4 m (height) [6,7]. The plat-fin type heat exchanger was adopted to enhance the heat transfer. During the heat discharging process, the air at the inlet of the adsorber was controlled at approximately 15 °C and 0.014 g water per gram dry sorbent by a dehumidifier. The available minimum temperature (T_{avl}) of the outlet air from the adsorber was preset to 30 °C. The data collection in the experimental study was achieved using the data acquisition system equipped with thermocouples, pressure sensors and flow meters located at the desired measurement points. The temperatures were measured by thermocouples with errors of ±0.1 °C. The air humidity was measured by a Vasala dew-point sensor with errors of ±3%. The operation of the experimental set-up was controlled by a PLC (Programmable Logic Controller).

The composite sorbents were first pelleted by using the binder and approximately 40 kg composite sorbents were then packed in the adsorber. The dynamic characteristic of the open-type adsorption thermal energy system packed with four kinds of composite sorbents (viz. CS1, CS2, CS3, and CS4) prepared by impregnating the mesoporous silica gel with the $CaCl_2$ solution with different concentrations [6,7] were investigated. Fig. 1 shows an example of the experimental and computational results of the temperature